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Ultrafast Graphene Photonics and Optoelectronics

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National Chiao Tung University

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14. ABSTRACT
Coupled surface plasmon modes of graphene on a plasma layer are studied. Three coupled plasmon modes are found, and analytical equations for their dispersion characteristics are given in the long-wavelength limit. Symmetric and antisymmetric modes are identified; between two strongly coupled modes, the antisymmetric mode is found to be more energetic than the symmetric mode. The great tunability of plasmon characteristics is shown by changing the surrounding dielectric constant, the coupling distance, and the plasma frequency of the substrate.

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Final Report for AOARD Grant FA2386-13-1-4022

"Ultrafast Graphene Photonics and Optoelectronics"

Date May 23th, 2016

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Abstract:

Coupled surface plasmon modes of graphene on a plasma layer are studied. Three coupled plasmon modes are found, and analytical equations for their dispersion characteristics are given in the long-wavelength limit. Symmetric and antisymmetric modes are identified; between two strongly coupled modes, the antisymmetric mode is found to be more energetic than the symmetric mode. The great tunability of plasmon characteristics is shown by changing the surrounding dielectric constant, the coupling distance, and the plasma frequency of the substrate. (Appl. Phys. Lett. 103, 201104 (2013))

Based on the understanding of coupled surface plasmon modes of graphene, a graphene-based terahertz plasmonic waveguide is proposed. The proposed structure benefits from the enhanced confinement and increased attenuation length of graphene surface plasmon by placing the graphene sheet in proximity of metal layers. (Appl. Phys. Lett. 105, 011604 (2014)). A graphene plasmon-based THz device is also fabricated and measured. The experimental results show a consistent trend between the plasmon resonance frequency and the grating period, as predicted by our theoretical analysis. (Submitted to Sci. Rep. (2016))

Introduction:

Graphene is a one-atom-thick 2D system that has a unique hexagonal crystal structure of two carbon atoms per unit cell. Unlike any other 2D semiconductor material known today, intrinsic graphene has a zero bandgap with its charged carriers behaving like Dirac fermions with a zero mass, resulting in many extraordinary properties that are very different from other materials. Due to the lack of the understanding of the graphene

plasmons and their interaction with the immediate surroundings, we investigated the coupled surface plasmon modes of graphene and graphene-based plasmonic devices.

Recently, we derived analytical models using Maxwell equations for coupled plasmon modes of structures that consist of a sheet of graphene and a plasma substrate such as a metal, a doped semiconductor, or another graphene layer. Using these models, various plasmonic devices with desirable characteristics can be designed, such as graphene-based waveguides and modulators. Examples of graphene-metamaterial hybrid system is shown in Fig. 1, where ϵ_d, ϵ_m, ϵ_1, ϵ_2, and ϵ_3 are the permittivities of the dielectric gap filling, the medium that is used to construct the metamaterial, the medium below the metamaterial, the medium below graphene, and the medium above graphene, respectively; $\boldsymbol{d_1}$ is the thickness of the metamaterial; $\boldsymbol{d_2}$ is the distance between the graphene sheet and the metamaterial; other structural parameters charactering the miniature patterns of the metamaterial are also specified, such as the width $\boldsymbol{w}$ and the height h of the engraved grooves. Depending on the design of the device, different types of the surface excitations can be induced. These excitations in turn give the desired functionality of the devices.

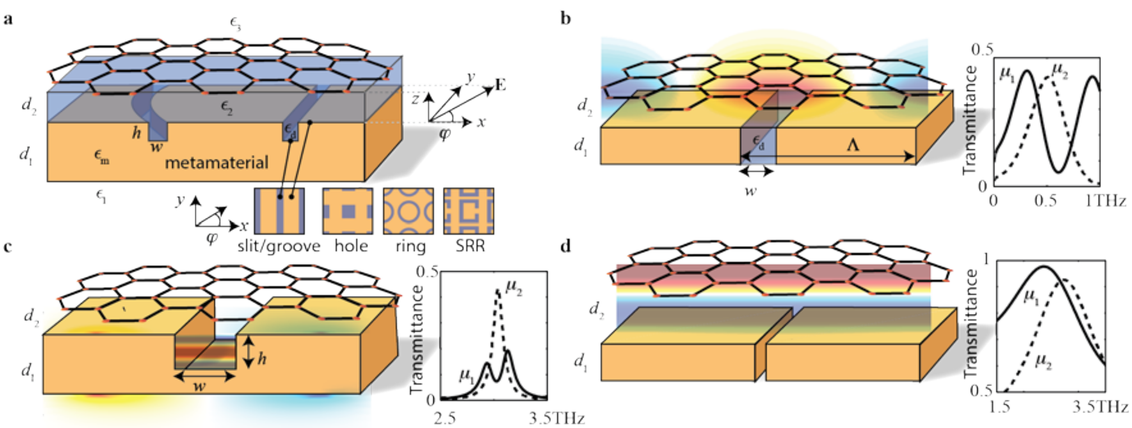

Fig. 1. Various excitations of graphene-based THz devices.

Experiment, Results and Discussion:

(1) Coupled surface plasmon modes of graphene in close proximity to a plasma layer (Appl. Phys. Lett, 103, 201104 (2013))

It has been shown that it is possible to fundamentally change the plasmon dispersion curve if substrate-induced effects are considered or if graphene is in close proximity with another plasma material, such as another layer of graphene, a metal layer, or a metal particle. The characteristic plasmon dispersion for the coupled plasmon modes of graphene that is 30 nm away from a doped semiconductor thin film are shown in Fig. 2. Three coupled plasmon modes ω_{sp1}, ω_{sp2} and ω_g are found with $\boldsymbol{\omega_{sp1} > \omega_{sp2} > \omega_g}$ (thick solid curves). The decoupled modes are also plotted as dashed curves for $d_1 = d_2 = 5\,\mu m$ between different layers of the structure; these modes are decoupled as long as the

plasmonic wavelength q^{-1} $d_{1,2}$. Two dashed lines are the surface plasmon modes associated with the top and bottom surfaces of the semiconductor substrate. Another rising dashed curve is the graphene plasmon mode. When $d_{1,2}$ q^{-1}, surface plasmon fields on the graphene sheet and on the semiconductor surfaces can hardly "see" each other; in this situation, the plasmon modes are weakly coupled, following the dashed curves in the high-*q* region. By contrast, the plasmon modes are strongly coupled in the limit $q \to 0$ when retardation is neglected, resulting in the solid dispersion curves that significantly deviate from the dashed curves. This situation is similar to the case of planar metallic waveguides where the surface plasmon mode on each surface are strongly coupled when $q \to 0$.

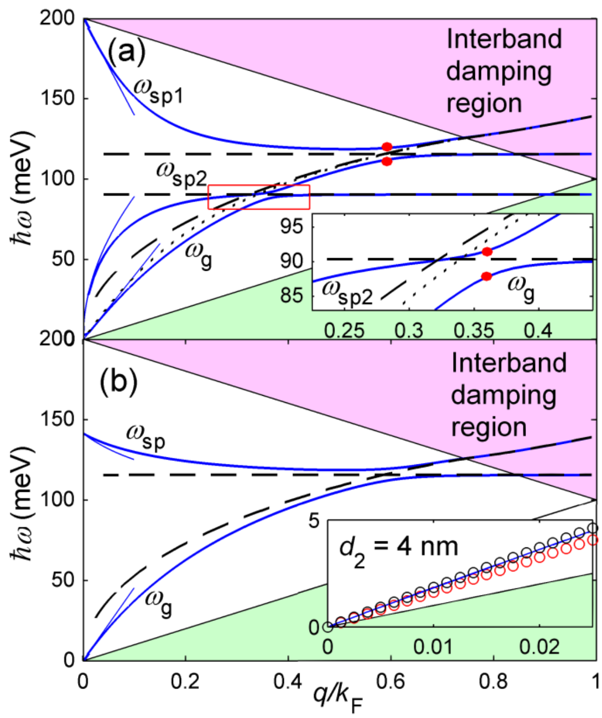

Fig. 2. (a) Coupled plasmon modes (ω_{sp1}, ω_{sp2} and ω_g, solid curves) of graphene 30 nm away from a semiconductor thin film of 50 nm thickness. (b) Coupled plasmon modes (ω_{sp1} and ω_g, solid curves) of graphene 30 nm away from a semi-infinite semiconductor substrate ($d_1 \to \infty$). Decoupled modes, calculated with $d_2 = 5\,\mu m$, are also plotted as dashed curves.

(2) Enhanced graphene plasmon waveguiding in a layered graphene-metal structure (Appl. Phys. Lett, 105, 011604 (2014))

In our previous work, we have shown that the surface plasmon dispersion of graphene is strongly modified by the presence of a plasma material such as a metal. In this study, we further show that within a certain spectral region the losses can be reduced when graphene is placed near a metal surface. The dispersion characteristics of surface

plasmons for the structure shown in Fig. 3(a) are plotted in Fig. 3(c). The curves are calculated using different values of $d_2 = d_3 = d$ marked next to each curve. As can be seen, the approximate analytical results (dashed curves) agree very well with the exact numerical results in the low-frequency region as long as the condition $q_1 d \ll 1$ is satisfied. In this region, the plasmon dispersion is a strong function of d; at a fix frequency, q_1 increases with decreasing d, signifying that the confinement of the plasmonic field can be consistently enhanced with decreasing graphene–metal distance. However, in the high-frequency region, all numerical curves merge into the blue curve because of the strong confinement of the plasmonic field on the graphene sheet: the presence of metal slabs becomes insignificant as the plasmonic wavelength becomes much smaller than the physical distances between the graphene sheet and the metal surfaces.

The attenuation length q_2^{-1} is plotted in Fig. 3(d) with the graphene–metal distance d marked next to each curve. As can be seen, the approximate analytical results (dashed curves) agree very well with the exact numerical results in the low-frequency region. In the intermediate-frequency region where q_1^{-1} is comparable to d, the black curves are below the blue curve, signifying reduced loss in the presence of the metal slabs. Therefore, as seen in Fig. 3(c) and Fig. 3(d), we find that an enhanced confinement and an increased propagation distance can be simultaneously achieved by the presence of the metal slabs within a certain spectral region.

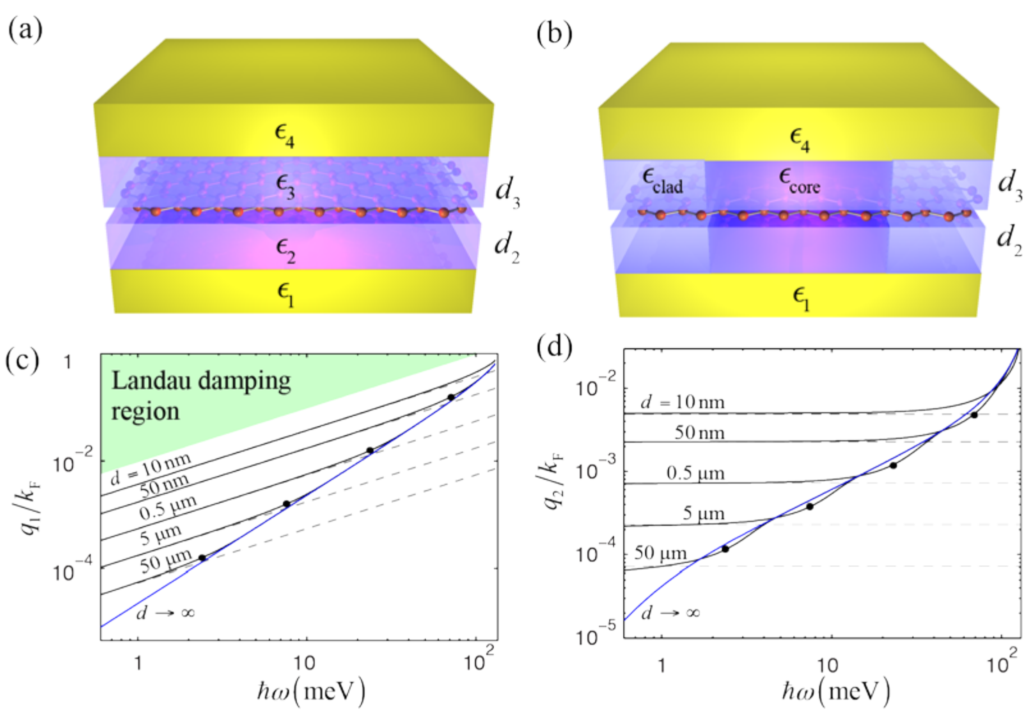

Fig. 3. (a) Planar waveguide, and (b) nonplanar rectangular graphene waveguide. (c) Dispersion characteristics and (d) the attenuation length of surface plasmons as a function of surface plasmon energy for the structure shown in (a) with $d_2 = d_3 = d$.

(3) Family of graphene-assisted resonant surface optical excitations for terahertz devices (submitted to Sci. Rep, (2016))

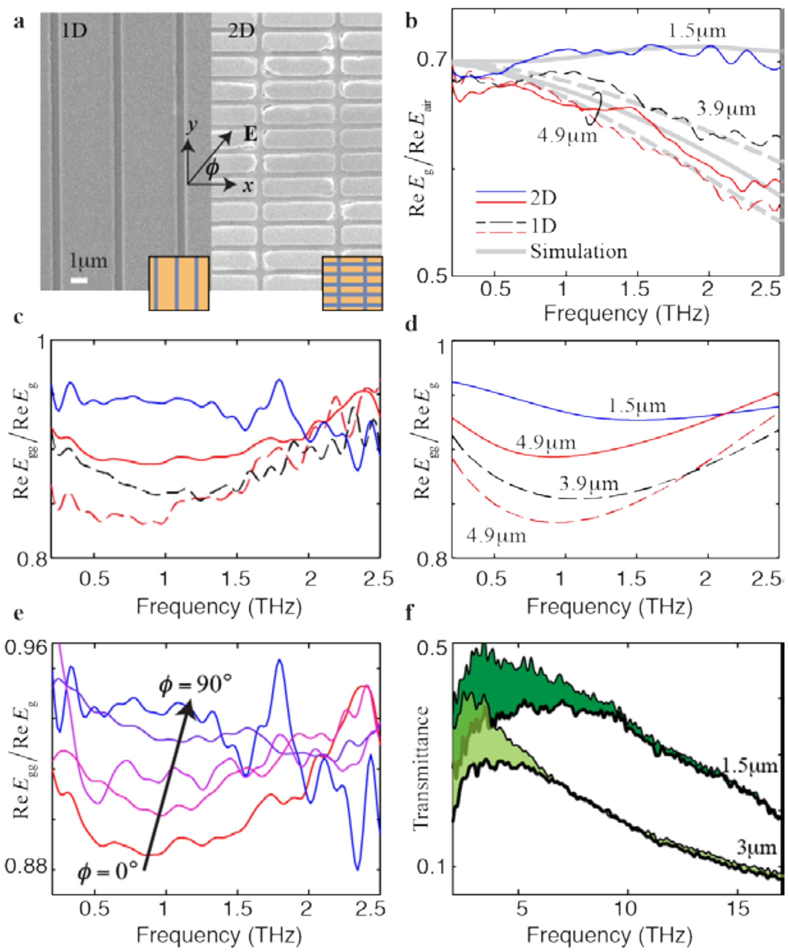

Fig. 4. (a) Images of scanning electron microscope for 1D and 2D gratings. (b) Ratio of the real part of the transmitted field through gratings to that of the free space without the grating. (c) and (d) are the simulated and experimental data of the transmitted field through graphene-grating structure, respectively. (e) Transmitted fields for different values of the polarization angle. (f) Transmittance measurement of FTIR for 1D gratings with (thick curves) and without (thin curves) graphene on top.

The majority of the proposed graphene-based THz devices consist of a metamaterial that can optically interact with graphene. This coupled graphene-metamaterial system gives rise to a family of resonant modes such as the surface plasmon polariton (SPP) modes of graphene. In this study, graphene SPP-based THz devices are fabricated and measured, as shown in Fig. 4(a). Terahertz time-domain spectroscopy (THz-TDS) is used to measure the transmitted electric field through the grating. The experimental and simulation results are plotted in Fig. 4(c) and Fig. 4(d), respectively. As can be seen, the plasmonic behavior is well described by the simulation. By rotating the angle from $0°$ to $90°$ for the 2D sample, as plotted in Fig .4(e), a smooth transition is shown for the curves

at different angles, indicating an angle-dependent scattering rate and the polarization-sensitive nature of our 2D structure. The effect of the Drude conductivity is observed using Fourier-transform infrared spectroscopy (FTIR), shown as the shaded areas in Fig. 4(f). Because the graphene SPP mode is supported by the Drude conductivity, the operational range of the graphene SPP-based THz device shown is limited not only by intrinsic Landau damping, but also by the frequency-dependent nature of the Drude conductivity of graphene.

List of Publications and Significant Collaborations that resulted from your AOARD supported project: In standard format showing authors, title, journal, issue, pages, and date, for each category list the following:

a) papers published in peer-reviewed journals,
b) papers published in peer-reviewed conference proceedings,
c) papers published in non-peer-reviewed journals and conference proceedings,
d) conference presentations without papers,
e) manuscripts submitted but not yet published, and
f) provide a list any interactions with industry or with Air Force Research Laboratory scientists or significant collaborations that resulted from this work.

Attachments: Publications a), b) and c) listed above if possible.

DD882: As a separate document, please complete and sign the inventions disclosure form.

Important Note: If the work has been adequately described in refereed publications, submit an abstract as described above and refer the reader to your above List of Publications for details. If a full report needs to be written, then submission of a final report that is very similar to a full length journal article will be sufficient in most cases. This document may be as long or as short as needed to give a fair account of the work performed during the period of performance. There will be variations depending on the scope of the work. As such, there is no length or formatting constraints for the final report. Keep in mind the amount of funding you received relative to the amount of effort you put into the report. For example, do not submit a $300k report for $50k worth of funding; likewise, do not submit a $50k report for $300k worth of funding. Include as many charts and figures as required to explain the work.

List of Publications and Significant Collaborations that resulted from your AOARD supported project: In standard format showing authors, title, journal, issue, pages, and date, for each category list the following:

a) papers published in peer-reviewed journals:

[1] **Journal name:** Physical Review B 86, 235446 (2012).
Title: Terahertz optical properties of multilayer graphene: Experimental observation of strong dependence on stacking arrangements and misorientation angles
Date: 2012/12/27
Authors: I-T. Lin, and J.-M. Li, K. Y. Shi, P. S. Tseng, K. H. Wu, C. W. Luo, and L.-J. Li

[2] **Journal name:** Appl. Phys. Lett. 103, 071103 (2013).
Title: Extremely confined terahertz surface plasmon-polaritons in graphene-metal
Date: 2013/8/13
Authors: X. Gu, I-T. Lin, and J.-M. Liu

[3] **Journal name:** Appl. Phys. Lett. 103, 081606 (2013).
Title: Surface polar optical phonon scattering of carriers in graphene on various substrates
Date: 2013/8/22
Authors: I-T. Lin and J.-M. Liu

[4] **Journal name:** Appl. Phys. Lett. 103, 201104 (2013).
Title: Coupled surface plasmon modes of graphene in close proximity to a plasma layer
Date: 2013/10/24
Authors: I-T. Lin and J.-M. Liu

[5] **Journal name:** IEEE J. Sel. Top. Quant. 20, 8400108 (2014).
Title: Terahertz Frequency-Dependent Carrier Scattering Rate and Mobility of Monolayer and AA-Stacked Multilayer Graphene
Date: 2014/1/1
Authors: I-T. Lin and J.-M. Liu

[6] **Journal name:** Appl. Sci. 4, 28 (2014).
Title: Terahertz Optoelectronic Property of Graphene: Substrate-Induced Effects on Plasmonic Characteristics
Date: 2014/2/7
Authors: I-T. Lin, Y.-P. Lai, K.-H. Wu, and J.-M. Liu

[7] **Journal name:** Nanomater. Nanotechnol. 4 (2014).
Title: Plasmonics in Topological Insulators
Date: 2014/4/1
Authors: I-T. Lin, Y.-P. Lai, K.-H. Wu, and J.-M. Liu

[8] **Journal name:** Appl. Phys. Lett. 105, 011604 (2014).
Title: Enhanced graphene plasmon waveguiding in a layered graphene–metal structure
Date: 2014/6/30
Authors: I-T. Lin and J.-M. Liu

[9] **Journal name:** Appl. Phys. Lett. 105, 06116 (2014).
Title: Optimization of double-layer graphene plasmonic waveguides
Date: 2014/8/5
Authors: I-T. Lin and J.-M. Liu

[10] **Journal name:** IEEE J. Sel. Top. Quant. 22, 1 (2016).
Title: Dispersion of Surface Plasmon Polaritons on a Metallic Grating
Date: 2015/11/30
Authors: I-T. Lin, C. Fan, and J.-M. Liu.

b) papers published in peer-reviewed conference proceedings

None

c) papers published in non-peer-reviewed journals and conference proceedings

None

d) conference presentations without papers

[1] **Conference name:** Physical Society Republic of China PSROC Annual Meeting (2013), NDHU, Hualien, Taiwan
Title: Terahertz optical conductivity of multilayer grapheme
Date: 2013/1/30
Authors: K. H. Wu, K.Y. Shi, P. S. Tseng, C. H. Kuo, H.-J. Chen, C. W. Luo, T. M. Uen, J. Y. Juang, J.-Y. Lin, T. Kobayashi, I. T. Lin, J. M. Liu, and L.J. Li

[2] **Conference name:** PSROC Annual Meeting, (2015) NTHU, Hsinchu, Taiwan
Title: Terahertz Conductance Spectroscopy Measurement of Gold Nanoparticles-Graphene
Date: 2015/1/28
Authors: Y.-S. Liu, C.-H. Lin, Y.-M. Chen, H.-J. Chen, C.-Y. Su, and K.-H. Wu

[3] **Conference name:** PSROC Annual Meeting, (2015) NTHU, Hsinchu, Taiwan.
Title: Preparation of Graphene- Metal Plasmonic Waveguide for THZ Optoelectronic Applications
Date: 2015/1/28
Authors: H.-C. Tsai, W.-T. Hsu, H.-J. Chen, K.-H. Wu, I.-T. Lin, J.-M. Liu

[4] **Conference name:** PSROC Annual Meeting, (2016) NSYU, Kaohsiung, Taiwan.
Title: Study Terahertz Surface Plasmon Polaritons in Graphene-Metal Nano Structure
Date: 2016/1/26
Authors: H.-J. Ho, K.-H. Wu, H.-C. Tsai, I.-T. Lin, J.-M. Liu

e) manuscripts submitted but not yet published

[1] **Journal name:** Sci. Rep. (2016).
Title: Family of graphene-assisted resonant surface optical excitations for terahertz devices
Date: 2016/3/1
Authors: I-T. Lin, J.-M. Liu, H.-C. Tsai, K.-H. Wu, J.-Y. Syu, and C.-Y. Su

[2] **Journal name:** IEEE J. Sel. Top. Quant. (2016).
Title: Propagating and Localized Graphene Surface Plasmon Polaritons on a Grating Structure
Date: 2016/4/1
Authors: I-T. Lin, C. Fan, and J.-M. Liu.

f) provide a list any interactions with industry or with Air Force Research Laboratory scientists or significant collaborations that resulted from this work.

None

4. Invited talks (event name, title, date):

[1] J.M. Liu, “Terahertz Graphene Photonics,” National Sun Yet-Sen University, Kaohsiung, Taiwan, July 18, 2013. (Invited Seminar Speaker.)
[2] J.M. Liu, “Terahertz Graphene Photonics,” National Cheng Kung University, Tainan, Taiwan, July 19, 2013. (Invited Seminar Speaker.)
[3] J.M. Liu, “Optoelectronic Properties and Plasmonic Devices of Graphene and

Topological Insulators," Northrop Grumman, Los Angeles, California, United States, February 11, 2015. (Invited Speaker.)

[4] J.M. Liu, "Lasers and Graphene Photonics," Industrial Technology Research Institute, Tainan, Taiwan, October 21, 2015. (Invited Speaker.)

[5] J.M. Liu, "Terahertz Graphene Photonics and Plasmonics," Academia Sinica, Taipei, Taiwan, October 30, 2015. (Invited Seminar Speaker.)

[6] J.M. Liu, "Terahertz Graphene Photonics and Plasmonics," National Taiwan University, Taipei, Taiwan, October 30, 2015. (Invited Seminar Speaker.)

[7] J.M. Liu, "Graphene Plasmonics for Terahertz Devices," National Cheng Kung University, Tainan, Taiwan, March 24, 2016. (Invited Speaker.)

5. Award for best paper, best poster (title, date):

None

6. Award of fund received related to your research efforts (name, amount, date):

None